# Introduction

Turing's automata theory and von Neumann's self-reproducing automata.

# Review

## Evolutionary Programming

## Genetic Algorithm

## Co-evolution

Selection pressure and co-evolutionary arms race. (Turner 95.)

## Artificial Life

### Cellular Automata:

# Adaptive coloration in Natural Organisms

# Mimicry

Henry W. Bates first published in 1862 his findings about the similarities and dissimilarities between Heliconiinae and Ithomiinae butterflies, after 10 years of research in the Brazilian rain forest. For the next hundred years, it simulated heated discussion among all groups of people, scientists, philosophers, theologians, teachers and amateur naturalists. Bates collected ninety-four pieces of butterfly. He grouped them according to their similar appearance. He found butterflies having similar appearance, exhibiting morphological features which point to completely different species even families. Out of the ninety four species sixty seven are now classified as Ithomiinae, while twenty seven of them are Heliconiinae.

Bates was not only amazed with these finding, he was also determined to find an explanation for it. He found that Heloconiids were extremely abundant and very conspicuously coloured. They also had slow mobility so easier to catch. He noted,

‘*Although they fly slowly and are fragile in construction and apparently have no means of defence, they occur in areas where insectivorous birds hunt in flocks.*’

But these butterflies are not killed by birds, so an assumption is made that these butterflies are unpalatable and any palatable butterfly species which has the capability of having similar appearance will succeed in surviving insectivorous birds. This also provoked the idea that some Pierids pretend to be Heliconiids and thus enjoy protection which is really deserved only by the unappetising Heliconiids.

## Batesian Mimicry

Repulsive animals, such as heliconiids are very conspicuously coloured. Having this noticeable property, they are easily recalled by predators. Their wing pattern works as a warning to them. Once a predator has the knowledge of their inedible and unpalatable property, they would probably never attempt to try it again. As this is true, if any organism within close family and species, but being edible and having a deceptive resemblance to those conspicuously coloured species will be avoided by the predators. expresses,

"Such unpalatable appearing and yet edible animals thus possess a false warning pattern, they 'act a part'. An actor is a mime, and so the representation of a false warning pattern was called mimicry. Since Bates was the first to point out this phenomenon, it has received the name *Batesian Mimicry* in his honour."

In general, the animal which is avoided by predator for unpalatable behaviour is called the **model** and the imitating animal is called the **mimic**.

An important concept in contained in the self-evident term ‘pattern’, or more exactly, warning pattern, camouflage pattern and protective pattern. Man orients himself mainly with his eyes and he therefore pays particular attention to visual stimuli. But many animals orient predominantly by smell also our previous discussion of colouration and morphological characters applies equally well to odurs (olfactory stimuli).

## Mullerian Mimicry

Bates was not able to explain some phenomenon of mimicry. Occasionally two inedible unrelated butterfly species are amazingly similar in appearance. An explanation for this was provided by Fritz Muller in 1878. When there are multiple inedible species it is hard for predators to recognize each of them to know which one to consume and which one to avoid. Because of predator's limited memory, all these species still lose their number even after being inedible. So to save this loss, and to prevent more sacrifice of their own kind, inedible species from different family also tend to evolve to have similar appearance. This phenomenon is referred to as Mullerian Mimicry in the name of Fritz Muller.

## Formation of Mimicry Rings

The set of morphologically different species having similar appearance is considered within a single mimicry ring. This ring constantly evolves. One reason being predators have limited memory, and also newly born predators take certain time for learning.

In discussing the formation of mimicry rings, makes an analogy to the way planets form.

"Like planets forming from a cloud of gas, clusters of mimetic species will arise, and form what we call mimicry 'rings'. Species occupying spaces in between the rings will be pulled into them, but sooner or later these focal patterns, having absorbed all the available species, will stabilize. If they differ too much from each other they will not be able to converge, for predators like birds will never mistake one for the other."

Regarding the dynamics of mimicry, discusses three different theories. Firstly, according to , and , evolution of rings happens in a slow gradual continual process. Secondly, and suggests that mimics are created in a single, final mutational step. Thirdly, a synthetic theory also called *two stage model* has been proposed, which originated by and . According to this theory, in the first step mimics get a very close resemblance to the model, which gets more accurate over time, having a more refined resemblance.

# Modeling the evolution of mimicry

## Past work

Various models of mimicry has been explored and modeled. The model of (Turner & Speed, Learning and Memory in Mimicry. I. Simulations of Laboratory Experiments, 1996) and the mathematical model of (Huheey, 1988) tend to focus on the selective pressure on prey brought about by the particular learning abilities of the predator, and employ simple Monte Carlo or mathematical approaches.

(Sherratt, 2002) provides an innovative perspective on the evolution of warning signals by considering coevolving predator and prey populations. The model's predators are deterministic, in that they have a fixed behavioural strategy over their lifetime, and cannot learn from experience. For both cryptic and conspicuous prey, each predator has fixed policy of either attacking or avoiding.

The latest work on modelling evolution of Warning Signals and Mimicry with Individual based simulation is done by Frank and Noble. Their initial work at (Franks & Noble, Conditions for the evolution of mimicry, 2002) seems of focus on putting some conditions of mimetic evolution in an individual based model with multiple species preyed upon by a single abstract predator, where the appearance of each prey species can evolve but their palatability is fixed.

On (Franks & Noble, The origins of mimicry rings, 2003) a new model for the origin of Mimicry ring has been proposed. Accordingly theory suggests that all Mullerian mimics in an ecosystem should converge into one large ring, while this convergence will be encouraged by presence of Batesian mimics. So and evolutionary simulation to observe the above mentioned phenomenon has been presented in this piece of work.

Frank & Noble continue to test the influence on mimicry ring evolution by Batesian mimics in their work on (Franks & Noble, Batesian mimics influence mimicry ring evolution, 2004).

### Huheey's Mathematical Model:

### Turner's Models:

### Sherratt's Model:

In this model the predators are deterministic, in that they have a fixed behavioural strategy over their lifetime, and cannot learn from experience.

### Models by Frank and Noble:

The first work by Frank and Noble is presented in (Franks & Noble, Conditions for the evolution of mimicry, 2002). In this model "multiple species are preyed upon by a single abstract predator; the appearance of each prey species can evolve but their palatability is fixed."

**Franks and Noble: The Origins of Mimicry ring**

Intro:

Model description:

Prey Genotype and Phenotype:

The model contains a population of prey species each having an appearance and palatibility level. Different species of prey were each assigned a fixed palatability level on a scale between zero and one (least to most palatable), where 0.5 is neutrally palatable. Palatale species have values greater than 0.5, and unpalatable species have values lower than 0.5. Each prey species has used two genes with values compositely representing their external appearance or phenotype. Both of these genes were constrained to values from 1 - 200. The Euclidean distance of one phenotype from another represented their level of similarity.

Predator genotype and phenotype:

Similar to (Turner, Kearney, & Exton, Mimicry and the Monte Carlo predator: the palatability spectrum and the origins of mimicry, 1984)'s stochastic model, predators were modeled with a Monte Carlo reinforcement learning system. The predator's experience of each phenotype was represented by an attack probability, which was initialized to ambivalence at 0.5. After eating prey of a particular phenotype, the predator would make a post-attack update of the relevant probability according to the palatability of the prey consumed. The predator would use its experience of different prey appearances to help it decide on whether or not to attack then at the next opportunity. Unlike the stochastic model,

Results:

## FormAL Framework

### Environment

### Spatial representation

### 3D Visualization

### Agents

### Mobility

## Mimic and Model

### Pattern representation by Cellular Automata

### Species diversity

Hamming distance between different CA patterns have been used to distinguish between species.

Franks and Noble have used different models to diversify species. In (Franks & Noble, Conditions for the evolution of mimicry, 2002) they have used linear difference in number "constrained to a 'ring' of values from 1-20 (where 20 and 1 are neighbours)" to distinguish species diversity. Here the distance of one phenotype from another represents their level of similarity.

### Genetic representation of palatability

The palatability of each prey species is fixed and has been represented with 2 bit of the genome giving it a range of 0 to 3 with four levels of palatability. The combinations are as follows:

|  |  |
| --- | --- |
| **Gene (Index 8 to 9)** | **Palatable** |
| 00 | True |
| 01 | True |
| 10 | False |
| 11 | False |

This representation is unlike (Franks & Noble, The origins of mimicry rings, 2003) where palatability level has been used on a scale between zero and one (least to most palatable), where 0.5 is neutrally palatable.

### Interaction between Mimics and Models

### Interaction with predators

## Predator

### Learning

#### Hebbian Learning

#### Hopfield Network

### Design of Memory with Hopfield Network

### Interaction and Reproduction

### Interaction with Models and Mimics

# Results and Analysis

Experiment 1: Initial configuration of two prey species:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Palatable) | 108 | Population | | 10 |
| Rule 30  (Unpalatable) | 108 |
| Reproduction | Age Limit | 100 | Reproduction | Age Limit | 500 |
| Interval | 1000 | Interval | 800 |
| Mutation Rate | Pattern | 0.05 | Mutation Rate | 0.3 | |
| Genome | 0.5 |
| Demise Age | 2000 | | Demise Age | 2000 | |
| Minimum Attack Age | 500 | |
|  |  |  | Memory Configuration | Minimum | 2 |
|  |  |  | Maximum | 10 |

The above set of parameters were carefully selected to be the initial condition for this run of the simulation. This test has been done with two sets of prey species with very different CA pattern and with opposite palatability and equal population. To control reproduction of the prey species their age limit has been set to 100 iterations into the time the species was alive. And the reproduction interval was set to 1000 iterations.

Pattern mutation rate has been set to a minimal level of 0.05 as by increasing this variable it is possible to increase the size of mimicry ring present in the simulation. The Genome mutation rate controls the rate at which genome of the child prey species will deviating from their parents. As mentioned earlier the genome mutation rate has been separated from the pattern mutation rate to bring more control to the number of mimicry rings generated.

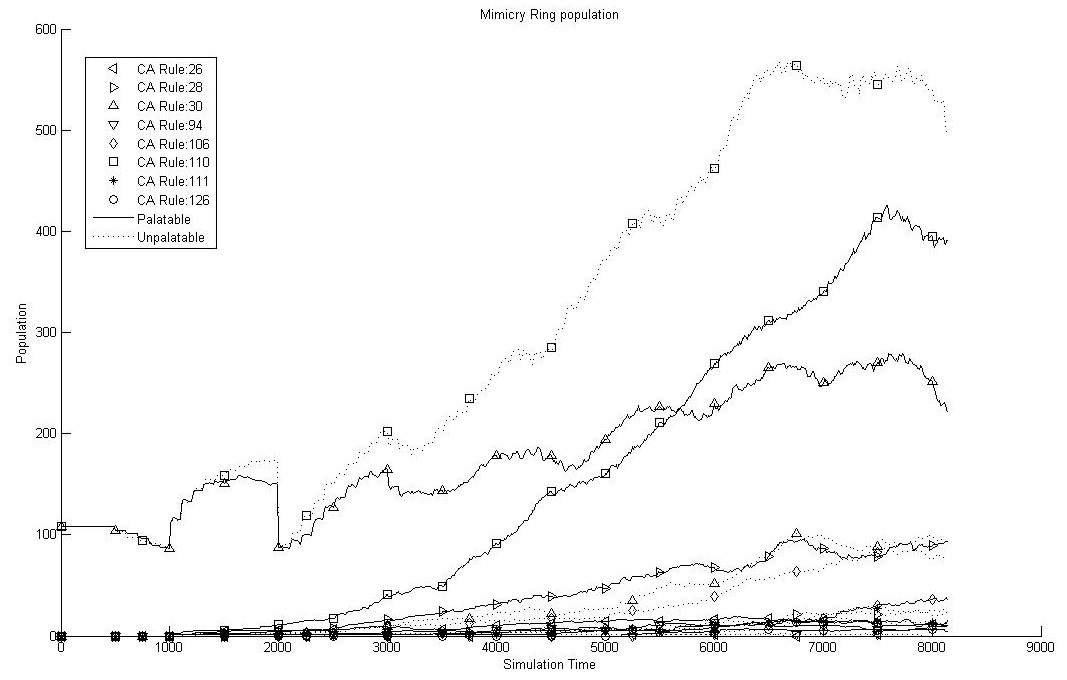
Prey demise age been kept to 2000 iterations similar to predator demise age. But later in the following results predator demise age has been increased to 5000 iterations. Predators in this simulation generates selection pressure for the evolution of mimicry. So the longer a predator is present in the simulation it will be making intelligent decisions in term to selecting which prey species to consume and which one to avoid. But with the current rate of demise for predator we were able to create successful mimetic population of prey species as we will see in the analysis in the following results.

Initial population of predator species has been set to 10 which is in accordance with the prey population in the simulation. The reason for such low rate of predator is unlike prey species which are consumed by predators, there is no cause of the predator species to die accept their natural cause of death, that is to reach their demise age. So predator population can explode very easily. That is why their population is controlled in a restrictive manner with the help of high reproduction age limit and reproduction age interval.

The memory configuration size for predators are a very interesting parameter. The minimum memory size is directly associated with the number of prey species with which we initiate the simulation. Otherwise evolution of mimicry is not observed. As mentioned earlier the minimum memory size is the number of prey species predator would consume before starting to make decisive consumption of prey species. After the initial birth of a predator and when the minimum attack age is crossed, it starts consuming prey species present in its vicinity without making any judgement. At this point its memory size is zero. As long as the minimum memory size is not reached predators will blindly consume prey species and insert their CA pattern and associated palatability into its Hopfield memory bank. No later than the minimum memory size has been reached predator will start making intelligent decision about consuming its prey species. When catching a prey if its memory tells that its palatable it will consume that prey. otherwise if memory recognizes it to be unpalatable predator will certainly let it go.

Now as we know the behaviour of Hopfield memory, a recognition result will always be achieved depending on the similarity of the patterns stored in memory. So when minimum memory size has been reached the predator will always make a decision based on the similarity of the prey pattern currently captured and the patterns stored in memory.

Simulation time: **8000 and above**



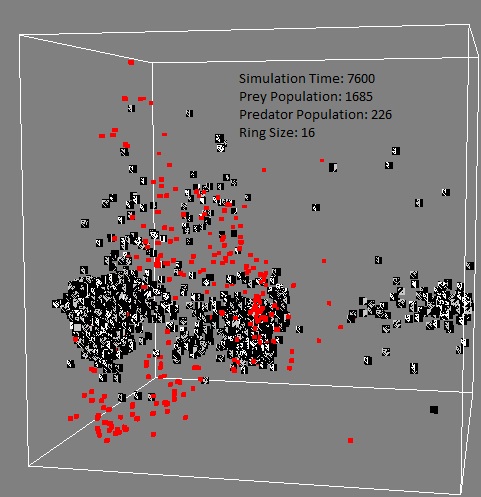
The above plot is simulation time verses prey population after running it for above 8000 iterations. With the initial configuration in the above table we can observe that multiple rings of prey population has been created. Two prey species are in a ring if their CA pattern have a hamming distance within 10 bits. Population of palatable species has been represented with straight curve while population of unpalatable species has been defined with the help of dotted curve. Difference signs of squares, triangles and diamonds have been used to distinguish between species of prey population. The simulation was initiated with two prey species having CA rule of 110 and 30 and being palatable and unpalatable consecutively.

By closely observing the graph we could see the population of the two species have started dropping at around time 500 when the initial predator population reaches the maturity for consuming prey species. At around time 1000 the prey population starts reproducing as the population increases. At around the same time different other species of prey population gets to be born with mutated CA patterns. Over time the population of CA Rule 110 dominates the population as most predators recognizes it as unpalatable. And similarly a population of CA Rule 110 or within the same ring of palatable species starts rising, while at one point overlaps the population of CA Rule 30 (Time: 5700 approx.) which was initially considered as a set of palatable species.

We can observe from the above results that the evolution of mimicry has taken effect. A population of mimics were successfully able to exceed the population of other prey species the reason being avoidance by predators of prey pattern similar to unpalatable ones. We can conclude that Batesian mimicry has taken effect in the simulation.

The above configuration is not the most appropriate condition for Mullerian Mimicry. Even though we can observe that a single pattern of unpalatable species dominate the entire population, still the prey population comes to a complete demise after 10,000 iterations, because of predator population explosion. This effect was fixed in the following configurations where we will see the continuous increment of prey and predator population and eventually behaviours of Mullerian mimicry, where all prey species converge to a single CA pattern.

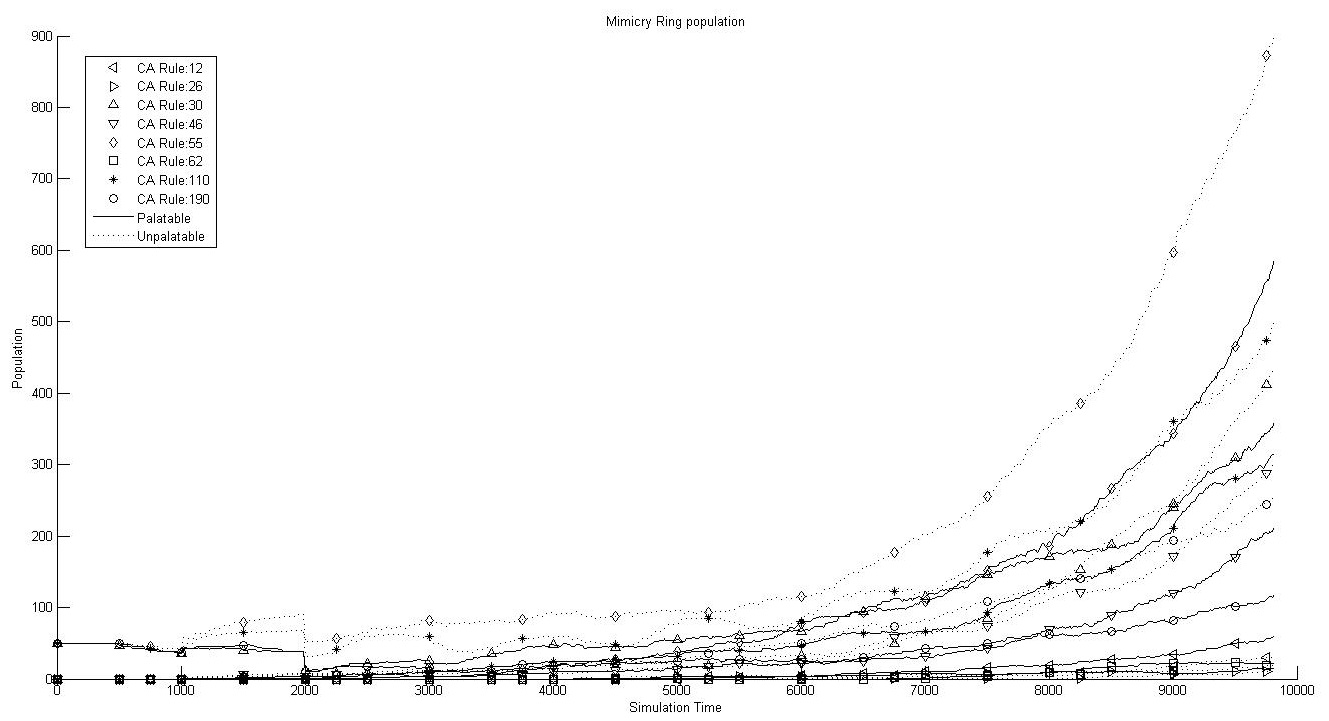
Simulation time: **7600 and onwards**



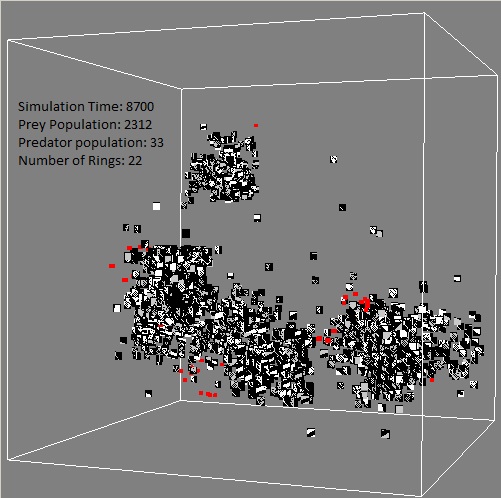
Experiment 2: Initial configuration with four prey species:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Palatable) | | 50 | Population | | 10 |
| Rule 30 (Unpalatable) | | 50 |
| Rule 55 (Palatable) | | 50 |
| Rule 190 (Unpalatable) | | 50 |
| Reproduction | Age Limit | | 100 | Reproduction | Age Limit | 500 |
| Interval | | 1000 | Interval | 1500 |
| Mutation Rate | Pattern | | 0.05 | Mutation Rate | 0.3 | |
| Genome | | 0.5 |
| Demise Age | 2000 | | | Demise Age | 2000 | |
|  |  |  | | Memory Configuration | Minimum | 4 |
|  |  |  | | Maximum | 10 |

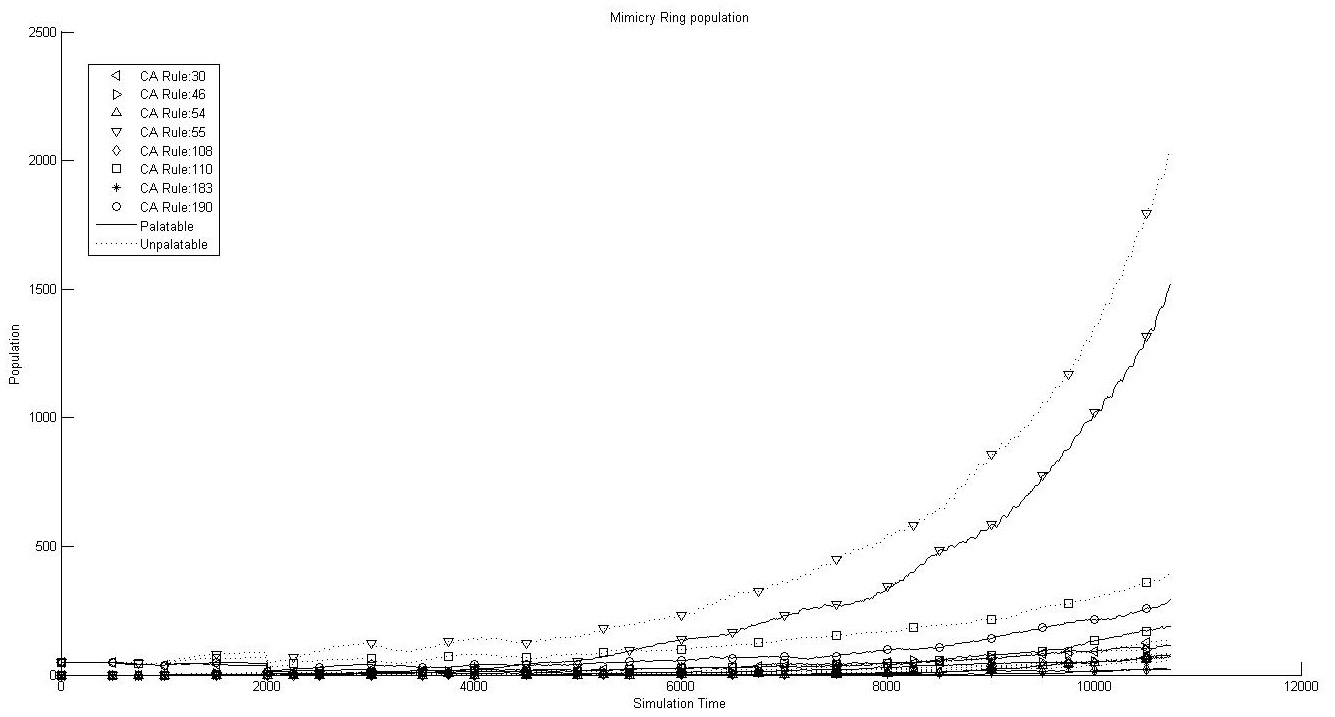
Simulation time: **9000 and onwards**



Simulation time: 9000 and onwards

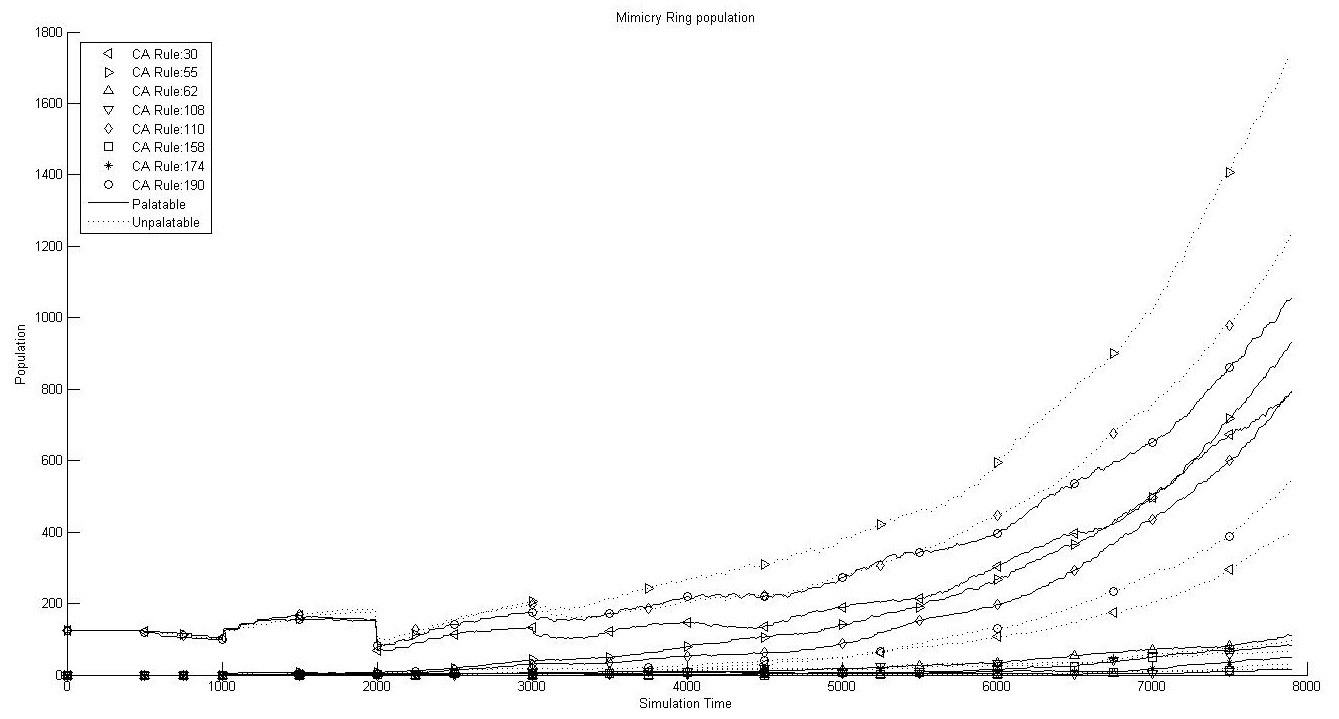


Simulation time: **10000 and onwards**



Increased initial population with four prey species:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Palatable) | | 150 | Population | | 10 |
| Rule 30 (Unpalatable) | | 150 |
| Rule 55 (Palatable) | | 150 |
| Rule 190 (Unpalatable) | | 150 |
| Reproduction | Age Limit | | 100 | Reproduction | Age Limit | 500 |
| Interval | | 1000 | Interval | 2500 |
| Mutation Rate | Pattern | | 0.05 | Mutation Rate | 0.3 | |
| Genome | | 0.5 |
| Demise Age | 2000 | | | Demise Age | 5000 | |
|  |  |  | | Memory Configuration | Minimum | 4 |
|  |  |  | | Maximum | 10 |



Increased initial population with six prey species:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Prey configuration** | | | **Predator configuration** | | |
| Population  (Cellular Automata) | Rule 110 (Palatable) | | 150 | Population | | 30 |
| Rule 30 (Unpalatable) | | 150 |
| Rule 55 (Palatable) | | 150 |
| Rule 190 (Unpalatable) | | 150 |
| Rule 57 (Palatable) | | 150 |
| Rule 105 (Unpalatable) | | 150 |
| Reproduction | Age Limit | | 100 | Reproduction | Age Limit | 500 |
| Interval | | 1000 | Interval | 2000 |
| Mutation Rate | Pattern | | 0.05 | Mutation Rate | 0.3 | |
| Genome | | 0.5 |
| Demise Age | 2000 | | | Demise Age | 5000 | |
|  |  |  | | Memory Configuration | Minimum | 4 |
|  |  |  | | Maximum | 10 |

Initial configuration with more unpalatable than palatable species.

Initial configuration with more palatable than unpalatable species.

Initial configuration with only palatable species.

Initial configuration with only unpalatable species.

Initial configuration with different set of CA rules.

Initial configuration with only one CA rule or a single prey species.

Initial configuration with predator motion slower than prey.

Initial configuration with prey population slower than predator.

Initial configuration with larger resolution of the prey CA pattern.

Increasing CA pattern diversity by changing pattern mutation rate.

initialize with a set of prey species with random patterns and then evolve with predator to observe the result.

Initialize predator decision to consume and not consume a prey species depending on palatability.

Initialize with same species of palatable and unpalatable ones and run the simulation. (should not take much effect to produce mimicry, can only establish that mimicry is sustainable).

# Application for the evolution of mimicry

Part of this thesis was to think about whether the evolution of mimicry can be used in a problem solving scenario similar to evolutionary programming or genetic algorithm as it is used to optimize solutions using mathematical functions. Predator-prey co-evolution has also been used for solving interesting problems (Hillis, 190), giving better result than conventional methodologies.

The biggest challenge faced while searching for the appropriate problem to be optimized is the idea of associating palatability with CA pattern with which the prey species has been represented. If we consider the CA pattern to be a certain solution to a problem then the set of 2D CA pattern among which the prey species vary could be considered as the solution set of the problem. And if we consider that the predator species are responsible for selecting the appropriate pattern based on their palatability, then we can consider palatability as the criteria for selection of the pattern (or the evaluation/fitness function for the case of Evolutionary Programming/Genetic Algorithm).

If the predator associates the CA pattern with palatability then it does not make any sense of having a **mimic** in the solution space as mimics will have the same pattern with opposite palatability. So using the evolution of mimicry to solve an optimization problem is futile if we try conventional problems which already can be solved with the help of evolutionary programming or genetic algorithm.

So the kind of problems we should be looking for applying the evolution of mimicry, are the ones which cannot be solved with conventional evolutionary methods. We should be looking for a problem where the idea of deception can be useful in term of solving it. Unfortunately during the time of this research we were unable to find such a problem.

# Conclusion

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